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Characteristics of impulsive VHF lightning signals observed by the FORTE satellite

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[1] We study very high frequency (VHF) and optical emissions from lightning, observed by the FORTE satellite, differentiating between impulsive (transionospheric pulse pairs (TIPPs)) and nonimpulsive events. TIPPs are seen to constitute 47% of the FORTE VHF data but only 32% of the optically coincident data. The median peak optical irradiance of the optical emission associated with TIPPs is 916 μW/m^2 at FORTE and for non-TIPPs is 195 μW/m^2. The median effective pulse width of the optical signal from TIPPs is 658 μs, and it is 548 μs for non-TIPPs. In the VHF, both event types have similar observed peak powers (0.086 mV^2/m^2 and 0.089 mV^2/m^2, for TIPPs and non-TIPPs, respectively). The optically coincident lightning (of either type) is weaker in peak VHF emission than is the lightning that lacks coincident optical signals, although for non-TIPPs, the stronger the VHF peak, the more likely the event is to have a coincident optical signal. For TIPPs, however, this is true only for events with peak $E^2 < 0.1$ mV^2/m^2. Above that threshold, TIPPs are increasingly less likely to show coincident optical emission with increasing VHF peak E^2. For both TIPPs and non-TIPPs, the peak current reported by the U.S. National Lightning Detection Network™ and peak VHF power reported by FORTE are statistically proportional. The nature of the proportionality appears to depend upon the polarity of the discharge but not upon the event type. We also find that only 11% of TIPPs are associated with negative-polarity discharges, compared to 75% of non-TIPPs. Finally, we find that TIPPs arise from events with altitudes of 6–15 km, although we see optical coincidence only for those TIPPs occurring above ~10 km. *INDEX TERMS:* 3334 Meteorology and Atmospheric Dynamics: Middle atmosphere dynamics (0341, 0342); 3304 Meteorology and Atmospheric Dynamics: Atmospheric electricity; 3359 Meteorology and Atmospheric Dynamics: Radiative processes; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; *KEYWORDS:* lightning, narrow bipolar events, optical emissions, VHF emissions, satellite observations

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1. Introduction

[2] The FORTE satellite, its radio-frequency (RF) and optical payloads, and observations of lightning using them have been presented in detail elsewhere [*Jacobson et al.*, 1999, 2000; *Suszcynsky et al.*, 2000, 2001; *Kirkland et al.*, 2001; *Light et al.*, 2001b]. One particularly prevalent signature in the FORTE very high frequency (VHF; 30–300 MHz) data is that of the pulse-pair. This type of event consists of two narrow VHF impulses separated in time by up to 150 microseconds; they are interpreted as being a single VHF impulse occurring within the cloud, which is seen by the satellite directly and in reflection off the Earth [*Holden et al.*, 1995; *Massey and Holden*, 1995; *Massey et al.*, 1998a, 1998b]. (These events have been dubbed "TIPPs," or transionospheric pulse pairs; we will continue to use this name to differentiate these in-cloud impulses from other VHF lightning observed by FORTE.) It is important to emphasize that while TIPPs are understood to be in-cloud events, the VHF events lumped under the title of "non-TIPPs" include both cloud-to-ground and in-cloud lightning signals, in particular a large population of temporally broad IC events [*Light et al.*, 2001b].

[3] In previous studies, a number of facts emerged regarding TIPPs. TIPPs are not uncommon, comprising approximately 40–45% of all VHF events collected by FORTE. Some TIPPs are also among the brightest VHF events seen by FORTE. *Light et al.* [2001b] noticed, however, that when the FORTE VHF receivers are slaved to record data only when an optical signal has already triggered the FORTE Optical Lightning System (OLS), TIPPs still occur in approximately 40% of the VHF data, but they are among the weakest VHF events recorded. The TIPPs in the optically slaved data would often not have triggered the VHF receivers on their own. The fact that TIPPs are so common leads us in this work to look more closely at them as a specific phenomenon, and in particular to examine the characteristics of their accompanying optical signals.

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2. General Biases in the Data

[4] Since launch in 1997, FORTE has observed several million VHF events. Depending upon how one selects the data, however, the resulting sample can have a number of different biases. Below we describe some different sample sets of FORTE VHF data, and describe the biases inherent in each set. In all data subsets, however, we do impose consistent selection criteria, and thus certain biases are unavoidable in all sets. First, we select only events in the VHF database which show high signal-to-noise ($\geq$30) in the event peak power as compared to the power of the background, after suppression of anthropogenic carrier signals. Second, the events as observed at FORTE have suffered dispersion by the ionosphere such that the component of the group delay due to the ionosphere varies as approximately $1/f^2$. We "de-chirp" the data to remove this effect, and this allows us to estimate the line-of-sight total electron content (TEC) of the ionosphere between the event and the satellite. We impose an acceptable TEC range of $0.5 \rightarrow 10 \times 10^{17} e$ / m^2. Also, we reject events which appear to be TIPPs, but whose secondary pulses are too weak for the classification to be credible (signal-to-noise < 10). Finally, we considered only the low-band (26–48 MHz) FORTE data, where the TEC can be more accurately computed, and where the VHF signal levels are higher.

[5] One bias that will affect all data subsets is that, in order for an event to be identified as a pulse pair by our processing software, the two impulses must be identifiable as separate. This means that in practice all identifications of pulse pairs are biased against finding pairs in which the individual impulses are temporally broad ($\gtrsim$ 10 μs), because two broad impulses will not be sufficiently resolved. Similarly, we are biased against finding TIPPs which occur near the limb of the Earth in the satellite's field of view, because in that geometry the impulses will be too narrowly separated in time (*Jacobson et al.* [1999], and see section 2.1 of this work).

[6] FORTE recorded 3.1 million VHF events between 1 January 1998 and 31 December 1999, 35% of which meet the quality criteria described here. We are therefore left with 1,076,103 VHF events in 1998 and 1999, 47% of which are TIPPs.

2.1. Biases in NLDN-geolocated VHF Database

[7] In general, the U.S. National Lightning Detection Network™ (NLDN) (owned and operated by Vaisala-Global Atmospherics, Inc.) is largely insensitive to in-cloud lightning, and the standard NLDN lighting data are carefully quality controlled and limited to minimize mislocated "outlier" events, employing specific criteria [*Cummins et al.*, 1998]. This study, however, uses NLDN data which have been reprocessed with relaxed criteria, and therefore contains a larger fraction of events which occurred completely within the cloud. For those events, the geolocation, polarity and peak current estimates provided by the NLDN are not useful. Therefore in this data subset we confine ourselves to consideration of events jointly observed by FORTE and the NLDN, and which the NLDN identified as being a stroke to ground. We must point out, however, that the observed FORTE VHF emission which is temporally associated with an event detected by the NLDN may or may not have originated specifically from the ground stroke detected by NLDN. The VHF emission FORTE observes as a TIPP, for example, we know to originate within the cloud, although the coincidence statistics [*Jacobson et al.*, 1999] indicate that the NLDN-stroke and FORTE-IC impulse are somehow related to one another. This means that while the geolocation reported by the NLDN is still valid for the ground stroke (to within approximately 1 km), it is somewhat less accurate as a geolocation for the TIPP seen by FORTE; rather, we know only that the TIPP occurred somewhere within the storm, so that the geolocation is good to a few tens of kilometers. *Jacobson et al.* [2000] determined that the false-correlation rate for events observed by both FORTE and NLDN within 300μs is only 2%, and therefore we will use the NLDN geolocations to determine nadir angles, from which in turn we can infer the TIPP emission height [*Jacobson et al.*, 1999].

[8] In comparing FORTE and NLDN data for the time periods of April through September 1998 and May through October 1999, we find 5840 events that FORTE and NLDN observed within 300μs of one another, when we account for time-of-flight and ionospheric delays, and when we have rejected FORTE events according to the aforementioned criteria. Overall, 26% of these NLDN-coincident data are TIPPs. Examination of the relative percentages of TIPPs and non-TIPPs in this database as a function of viewing geometry shows that at nadir angles exceeding 58 degrees (where 0 implies the event was directly below the satellite, and the FORTE/VHF field-of-view extends to 63 degrees), the percentage of events identified as TIPPs dramatically falls off (Figure 1). This is because the primary and reflected pulses, when viewed so obliquely, are no longer separable, and therefore we cannot identify the event as a pulse pair. Thus we further culled this data set to include only the 3542 events which occurred less than 58 degrees from the satellite's nadir direction, and which can therefore be reliably identified as pulse-pairs or non-pulse-pairs. Of these, 1090 (31%) are identified as TIPPs. In the entire VHF database we saw that 47% of events were TIPPs.

[9] Another detection bias involves the $1/r^2$ falloff in power as the signal propagates towards the satellite. Weaker signals from the horizon will not, by the time they reach the satellite, be sufficiently strong to satisfy the VHF multi-channel-trigger criteria. Thus, events in the database at large nadir angle have been selected to be stronger (on average) than events occurring below the satellite, figured at the source. However, TIPPs are typically stronger in peak VHF power on average than are non-TIPPs (see Table 1). Their higher peak power renders them less susceptible to this bias; consequently the at-source peak power of TIPPs does not appear to vary with nadir angle, as shown in Figure 2. In contrast, the at-source peak power of non-TIPPs does increase for events seen from the horizon, implying that the weaker non-TIPPs are affected by the $1/r^2$ bias. (We have inferred the at-source peak VHF power as described in section 3.2.)

2.2. Biases in Optically Geolocated VHF Database

[10] This database consists of events for which VHF and both optical sensors on board FORTE separately triggered, giving us a geolocation (from the FORTE/OLS CCD

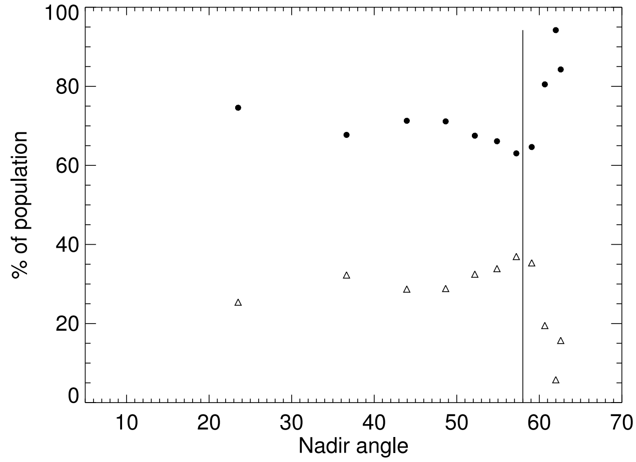

Figure 1. For the NLDN/FORTE coincident data subset, the percent of events which are identified as TIPPs (triangles) and non-TIPPs (circles) as a function of the nadir angle (0 degrees is directly below the satellite). The vertical line indicates the angle at which we apparently can no longer distinguish between TIPPs and non-TIPPs. (The data have been grouped in bins of nadir angle such that each angular bin covers an equal area on the ground.)

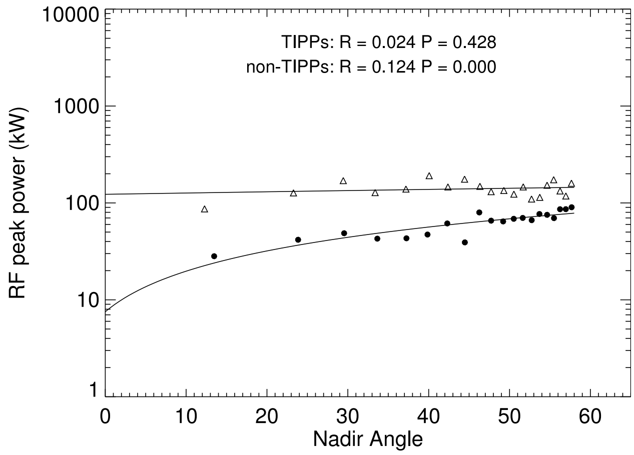

Figure 2. For the NLDN/FORTE coincident data subset, the at-source VHF peak power (assumed isotropic) in kilowatts as a function of nadir angle, differentiating between TIPPs (triangles) and non-TIPPs (circles). Events with nadir angles exceeding 58 degrees have been excluded from the data. Simple, linear-least-squares line fits are shown. For clarity, the data have been grouped in nadir angle such that each plotted point represents an equal area on the ground. (The lines were fit to all the data, not merely to the binned points.) The correlation coefficient, R, and probability of achieving that value of R in the null hypothesis are shown for each line.

imager), an optical waveform (from the FORTE/OLS photodiode detector), and the VHF data. This is a smaller database, with only 3139 events, 37% of which are TIPPs. All the previously discussed biases operate in this data subset, as well, with the caveat that the FORTE/OLS field-of-view has only a 40° half-angle. Hence, the $1/r^2$ effect is less pronounced. Similarly, in this data we do not have events which occurred near the limb of the Earth, and therefore we do not have any problems discriminating between TIPPs and non-TIPPs.

3. Results and Statistics

3.1. 1998–1999 VHF Database

[11] FORTE recorded 3.1 million VHF events between 1 January 1998 and 31 December 1999, but only 35% of them (1,076,103) meet the quality criteria described in section 2. 47% of these events are TIPPs. The distribution of peak observed (at-satellite) VHF E^2 for the two types of event are nearly identical, with equal medians (0.086 mV^2/m^2 and 0.089 mV^2/m^2 for TIPPs and non-TIPPs, respectively). However, when we examine the percentage of events that are TIPPs or non-TIPPs as a function of the peak observed E^2, we find that TIPPs are overrepresented among very strong events (Figure 3): while 47% of all events are TIPPs, ~70% of the strongest events are TIPPs. A more detailed understanding of the characteristics of TIPPs requires knowledge of the event geolocations or of some supplemental data for each type of event.

[12] Table 1 lists a few gross statistics for the entire VHF database from 1998–1999, as well as the two geolocated data subsets.

3.2. NLDN-Geolocated VHF Database

[13] As discussed in section 2.1, the peak current estimate reported by NLDN for the ground stroke associated with a TIPP is not expected to be a meaningful physical characteristic of the TIPP itself, as the VHF impulse observed as a TIPP is not the same discharge as the stroke to ground detected by NLDN. Nevertheless, we see in Figure 4 that the peak VHF E^2 and NLDN-estimated peak current ampli-

Table 1. Gross VHF Statistics for the Data Sets Described in the Text[a]

			TIPP Peak E^2		Non-TIPP Peak E^2	
	Number of Events	Percent That Are TIPPs	At-Satellite, mV^2/m^2	At-Source, kW	At-Satellite, mV^2/m^2	At-Source, kW
1998–1999 VHF data	1,076,103	47	0.086	—	0.089	—
1998–1999 VHF data with coincident PDD	9957	32	0.12	—	0.18	—
April–Sept. 1998 and May–Oct. 1999 VHF data with coincident NLDN	3542	31	1.4	84	0.54	29
1998–1999 VHF data with coincident optical PDD and LLS	3139	37	0.13	4.0	0.19	6.3

[a]Median values are given.

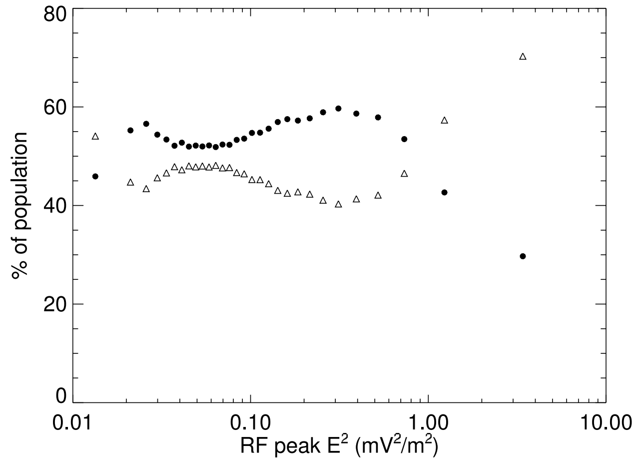

Figure 3. For all VHF events detected by FORTE in 1998–1999 which meet the selection criteria outlined in section 2, the percent of events which are identified as TIPPs (triangles) and non-TIPPs (circles) as a function of the observed (at-satellite) VHF peak E^2 (mV^2/m^2). (The data have been sorted by E^2 and binned such that each point plotted is the median peak E^2 of an equal fraction of points in the total database.)

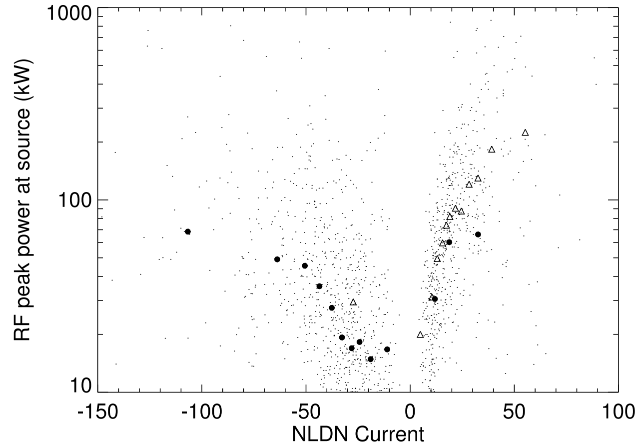

Figure 4. For the NLDN/FORTE coincident data subset, at-source peak power versus NLDN-reported vertical current amplitude. Events for which NLDN did not report a current are not shown. The data have been sorted by NLDN current and binned such that each large plot point is the median peak power and median current of an equal fraction of points in the total database. Triangles indicate TIPPs, and circles indicate non-TIPPs. The small dots are the un-binned data.

tude are statistically proportional, although the scatter in the relationship is considerable. Because the NLDN and FORTE VHF, in the case of TIPPs, are sensitive to different physical processes, the meaning of this correlation is unclear. However, in the NLDN-coincident data, the median observed (at satellite) VHF peak E^2 is 1.4 mV^2/m^2 for TIPPs and 0.54 mV^2/m^2 for non-TIPPs, and we believe that the median observed E^2 values are much higher in this database than for the VHF database as a whole (see Table 1) because the requirement of NLDN coincidence has preferentially selected the strongest VHF events.

[14] We can infer the at-source peak power in Watts for these geolocated events, assuming the radiation was isotropic and suffered no losses, and where we use the impedance of free space, 377Ω.

$$P_{VHF}(W) = \frac{E_{VHF}^2\left(\frac{V^2}{m^2}\right)4\pi R^2}{377} \tag{1}$$

The median at-source peak power is 84 kW for TIPPs and 29 kW for non-TIPPs in this data subset. Again we find that TIPPs are overrepresented among the strongest events (Figure 5).

[15] The altitude of the impulsive event giving rise to an observed TIPP is calculated using the event geolocations [*Jacobson et al.*, 1999]. The emitter-height distribution, shown in Figure 6, of the TIPPs in this NLDN-geolocated FORTE data subset shows a broad range of altitudes, with the majority of events occurring between 6–15 km. *Smith et al.* [1999] used a different method to determine emitter heights for a special class of in-cloud strokes, narrow bipolar pulses (NBP) [*Le Vine*, 1980; *Willet et al.*, 1989], using Los Alamos Sferic Array E-field change data. The altitude distributions of NBPs differ significantly depending on whether the NBP is of negative or positive polarity. NBPs are characterized by narrow, large amplitude bipolar electric field changes, associated with powerful, broadband high radio frequency emission; they are isolated from other radio signals by a few milliseconds; and they appear to arise from compact (100s of meters), vertically oriented channels [*Smith et al.*, 1997; *Smith*, 1998]. The emitter-height distribution for positive bipolars matches that of the general TIPPs shown here, while negative bipolars occur typically

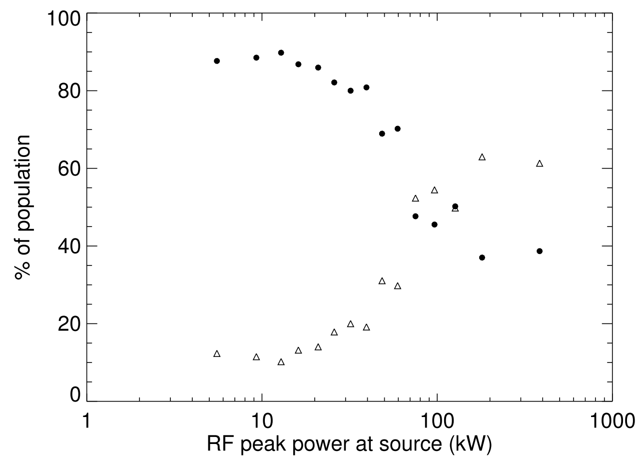

Figure 5. For the NLDN/FORTE coincident data subset, the percent of events which are identified as TIPPs (triangles) and non-TIPPs (circles) as a function of the the at-source VHF peak power in kilowatts, inferred assuming isotropic emission. Events occurring at nadir angles exceeding 58 degrees have been excluded from the data. (The data have been sorted by peak power and binned such that each point plotted is the median peak power of an equal fraction of points in the total database.)

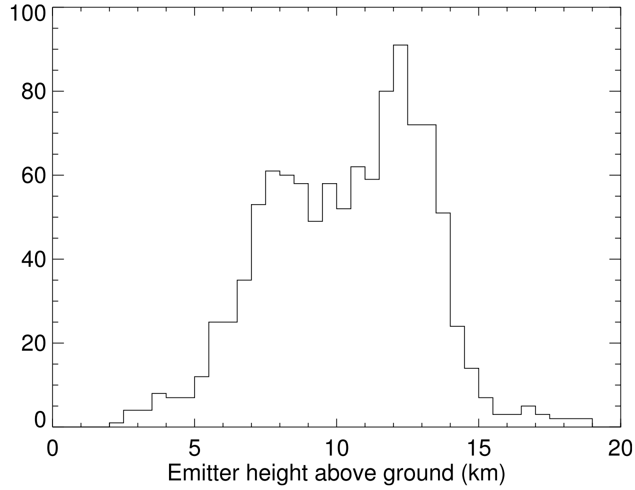

Figure 6. For the NLDN/FORTE coincident data subset, the distribution of TIPP heights above ground.

at altitudes of 15–21 km. *Shao et al.* [1996] and *Smith et al.* [1996] presented evidence that TIPPs and NBPs arise from the same processes, which is consistent with this TIPP height distribution, if TIPPs are associated mainly with positive NBPs.

[16] The NLDN peak current estimates for these events verify that TIPPs are overwhelmingly the result of positive polarity events, as shown in Figure 4. Only 11% of TIPPs are associated with negative discharges, compared to 75% of non-TIPPs. Figure 4 also shows that regardless of polarity or event type, the bin-median NLDN-estimated peak vertical current and bin-median VHF peak power are statistically proportional.

3.3. Optically Geolocated VHF Database

[17] In the optically coincident VHF data, the median detected VHF peak E^2 at the satellite is 0.13 mV^2/m^2 for TIPPs and 0.19 mV^2/m^2 for non-TIPPs. The median at-source peak power is 4.0 kW for TIPPs and 6.3 kW for non-TIPPs in this data subset. Compare this, in Table 1, to the at-source power of NLDN-detected events. In particular, notice that in the optically coincident VHF data, TIPPs are weaker than the non-TIPPs.

[18] In Figure 7a we examine the distribution of each type of event with nadir angle. The field-of-view of the FORTE/OLS is just ±40° from the satellite, and so covers only a small portion of the ground area seen by the FORTE VHF receivers. In the NLDN-geolocated data subset, it did not appear as if TIPPs were biased against detection from the limb by $1/r^2$ losses, even at nadir angles exceeding 40. Nevertheless, this optically geolocated data does suggest such a bias. However, Figures 7b and 7c show that neither optical nor VHF power increases for TIPPs observed from large nadir angles, as we would expect if the weaker events were specifically excluded from the data. Thus we assume the apparent trend in Figure 7a is not a $1/r^2$ detection bias. Figure 8 is the optically geolocated analog to Figure 5 in showing the relative TIPP/non-TIPP distribution as a function of at-source VHF peak power. We see that (1) this optically coincident data does not include the strongest VHF events seen previously and (2) the TIPPs are increasingly underrepresented at higher peak power, which is precisely opposite to the trend in Figure 5.

[19] Figure 9 shows the distribution of TIPP emission heights for this data subset, overlaid with the altitude distribution of the NLDN-geolocated data subset. We see that the optically coincident TIPP data lacks events occurring below 10 km, relative to the NLDN-coincident data. One might attempt to explain this height distribution simultaneously with the lack of optically detected strong VHF TIPPs, by hypothesizing that the strongest TIPPs occur preferentially at lower altitudes. The consequent optical attenuation would cause these strongest impulsive VHF events to therefore be excluded from this optically coincident database. However, in Figure 10 we see that this is not the case; there is no emission-height-dependence to the VHF peak power. The NLDN-coincident VHF powers are simply stronger than the optically coincident VHF powers, at all altitudes. There is, in fact, a slight trend for

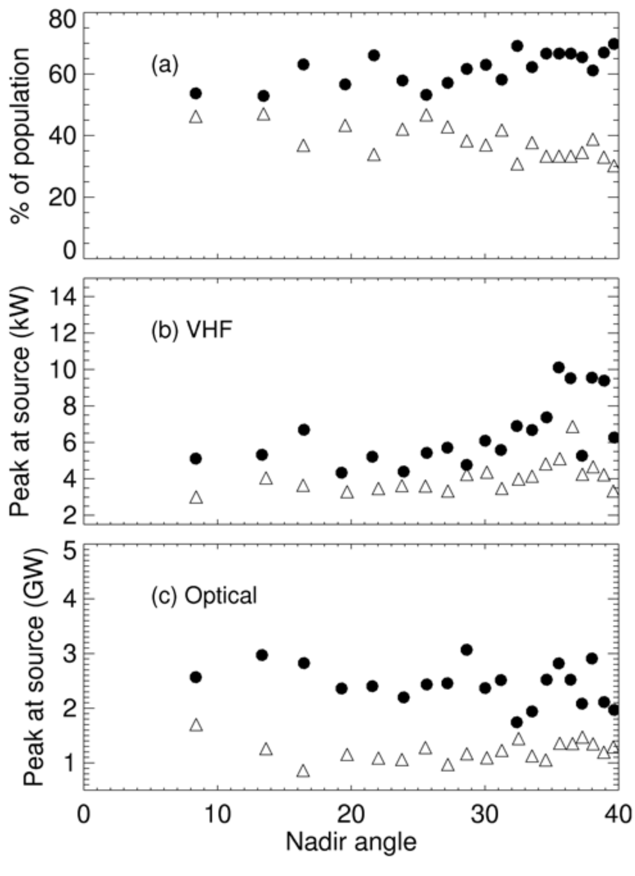

Figure 7. For the optically geolocated data subset, we have grouped the data by nadir angle such that each point covers an equal area on the ground, with median values plotted for TIPPs (triangles) and non-TIPPs (circles). Figure 7a shows the percentage of each type of event in the database. Figure 7b shows the peak inferred VHF power at the source. Figure 7c shows the peak inferred optical power at the source. (The data have been sorted and binned in nadir angle such that each plotted point represents the median values for data covering an equal area on the ground.)

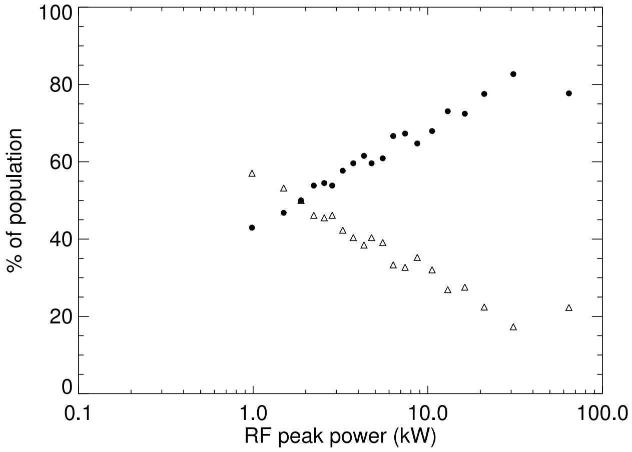

Figure 8. For the optical/VHF coincident data subset, the percent of events which are identified as TIPPs (triangles) and non-TIPPs (circles) as a function of the the VHF peak power in kilowatts, inferred assuming isotropic emission. (The data have been sorted by peak power and binned such that each point plotted is the median peak power of an equal fraction of points in the total database.)

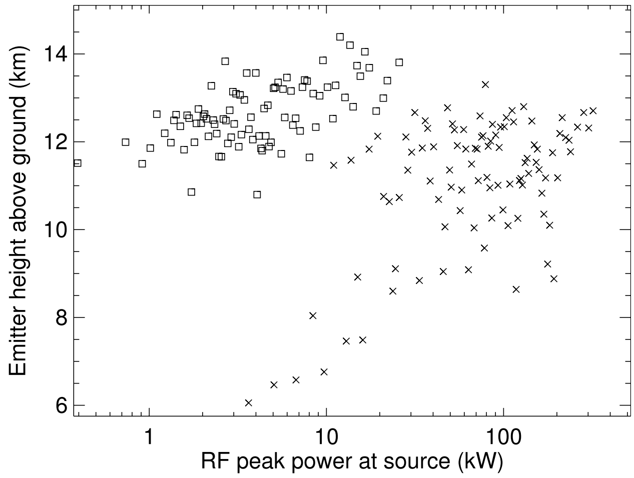

Figure 10. The inferred, at-source, VHF peak powers of TIPPs versus their heights above ground, for events in the optically coincident data subset (squares) and in the NLDN/FORTE coincident data subset (crosses). The data have been sorted by VHF power and plotted such that each point represents the median values for a group of 10.

TIPPs with higher VHF peak power to occur higher in the cloud.

[20] We know a significant amount of in-cloud lightning occurs at altitudes below 10 km [e.g., *Mazur et al.*, 1984; *Williams et al.*, 1989], and therefore conclude that the lower-altitude events are not seen by FORTE because those events are more deeply embedded within cloud, where the optical scattering losses are more severe [*Light et al.*, 2001a; *Koshak et al.*, 1994; *Thomason and Krider*, 1982]. Thus, the FORTE/OLS detection efficiency is effectively degraded for events occurring at lower altitudes. The FORTE/OLS consists of a photodiode detector (PDD) and the Lightning Location System (LLS), a 128 $\times$ 128 pixel CCD array. The LLS consists of a front-end optical assembly, a fixed-position CCD focal plane assembly with drive electronics and an operations and signal processing module (developed by Sandia National Laboratory) for lightning data discrimination. The front-end optical and CCD assemblies are identical to those used on the Lightning Imaging Sensor (LIS) developed by the National Aeronautics and Space Administration/Marshall Space Flight Center (NASA/MSFC). *Ushio et al.* [1999] presents simultaneous observations of in-cloud lightning by LIS and the Lightning Detection and Ranging (LDAR) system at Kennedy Space Center in Florida. That distribution peaks at 10 km and extends down to 7 km altitude. This discrepancy between the apparent minimum altitudes observed by FORTE and LIS is either due to the fact that *Ushio et al.* [1999] observed a Florida storm which was, overall, at a lower-than-average altitude (whereas the data in this study include storms nationwide, at all altitudes), or because the LIS detection efficiency is somewhat better than the FORTE/LLS.

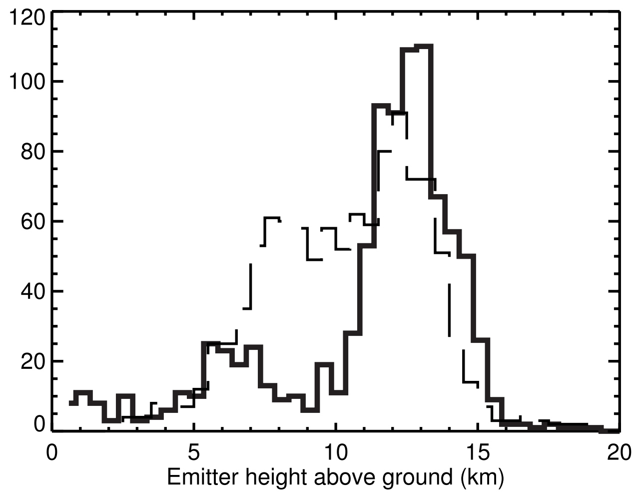

Figure 9. Distribution of TIPP event height above ground, for the optically coincident TIPPs (solid line) and NLDN-coincident TIPPs (dashed line).

3.4. PDD/VHF Coincident Data (Without Geolocation)

[21] Last, we examine the optical characteristics of all PDD data, compared to that PDD data for which there is VHF coincidence. The difference between this data subset and that described in section 3.3 is that we do not require the LLS to trigger, and therefore lack geolocation, but have a larger data set to study.

[22] In 1998–1999, there were 1,076,103 VHF events which met the selection criteria outlined in section 2, and there were 1,080,344 PDD records. From these two sets, 9957 PDD/VHF coincidences were identified, 3224 (32%) of which are TIPPs. The median peak optical irradiance at the satellite for all the PDD events (with or without VHF coincidence) is 91 $\mu W/m^2$. For the VHF-coincident data, the median optical peak is 96 $\mu W/m^2$ for TIPPs and 195 $\mu W/m^2$ for non-TIPPs. The effective width of the optical pulses is defined as the integrated intensity divided by the peak irradiance of the pulse, and is the width the pulse would have, were it rectangular. The median effective width of the optical pulses associated with TIPPs is 658 μs, compared to 548 μs for non-TIPPs. These findings are consistent with

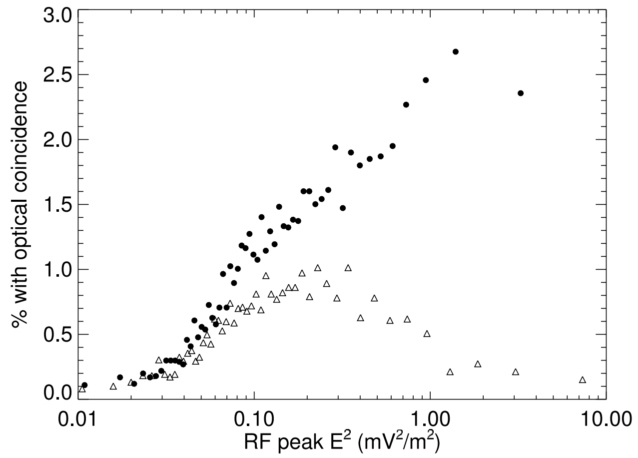

Figure 11. The percentage of VHF TIPPs (triangles) and non-TIPPs (circles) that have a coincident optical signal observed by FORTE, as a function of peak E^2. The data have been sorted by E^2 and plotted such that each point represents the median E^2 for a group of 10,000 points in the total VHF database and the percentage of those 10,000 that have an optical counterpart.

those of *Light et al.* [2001b], who saw that the weakest optical emission was from impulsive, in-cloud lightning, and that the optical emissions from in-cloud lightning were much more temporally extended than were those from ground strokes.

[23] The most striking difference between TIPP and non-TIPP characteristics is shown in Figure 11. The stronger the (at-satellite) VHF peak E^2 of a non-TIPP event, the more likely it is to have a coincident optical signal. In sharp contrast, the stronger a TIPP is, the less likely it is to have a coincident optical signal, if the observed VHF peak is greater than 0.1 mV^2/m^2. Below this threshold, the likelihood of optical coincidence increases roughly the same for TIPPs and non-TIPPs.

4. Summary and Discussion

[24] The light from optical emissions coincident with TIPPs is apparently just strong enough that FORTE sees only those events that occur above 10 km in cloud; those occurring at lower altitudes are apparently attenuated by scattering. The altitude cutoff is surprisingly clear, considering that the data includes all sorts of storms, with clouds having a wide range of altitudes and optical depths. The peak optical irradiance (at-source) is a factor of two lower for TIPPs than for non-TIPPs, and the effective pulse widths of optical emissions associated with TIPPs are 20% larger than those associated with non-TIPPs. These findings are consistent with the non-TIPP category of lightning containing a large fraction of ground strokes, which are optically very bright and narrow [*Light et al.*, 2001b].

[25] Using NLDN coincidence to find the polarity and peak current of the cloud-to-ground strokes associated with the observed FORTE VHF events, we found that the peak current and peak VHF power are statistically proportional to one another, regardless of the type of VHF event seen or the polarity of the NLDN-observed discharge. The slope of the proportionality, however, appears to change for positive and negative events. Because the NLDN and FORTE/VHF receivers are sensitive to different physical processes, the meaning of this relationship is unclear. TIPPs were found to be associated with positive polarity discharges 89% of the time. Previous authors have suggested that TIPPs are associated with a type of narrow positive bipolar pulse, and indeed we find that TIPPs appear to have the same height distribution as positive NBPs, as well as being associated with positive discharges.

[26] From the gross statistics of FORTE-observed VHF events in 1998–1999, we have seen that TIPPs are stronger VHF emitters, at the source, than are non-TIPPs, based on the NLDN-coincident data, by nearly a factor of three in power. However, TIPPs with coincident optical signals are 50% weaker than non-TIPPs with coincident optical signals. Further, TIPPs with optical signals are more than a factor of 20 weaker in VHF emission at the source than TIPPs coincident with NLDN strokes. Non-TIPPs with optical emission are five times weaker than non-TIPPs coincident with NLDN strokes. To summarize, we can say that optically coincident lightning is significantly weaker in peak VHF emission (figured at the source) than is lightning without light, as observed by FORTE. This trend is far more pronounced for TIPPs (by a factor of four).

[27] TIPPs constitute roughly 40% of VHF events seen by FORTE, although the percentage increases with peak observed E^2. However, the stronger the TIPP, the less likely it is to be accompanied by light. In particular, there is a marked down-turn in the probability of seeing light from a TIPP, at approximately $E^2 > 0.1$ mV^2/m^2. The converse is true for non-TIPP events, which are increasingly likely to have a coincident optical signal with increasing VHF peak.

[28] There are three plausible reasons we might see no light from strong TIPPs. First, it is possible that stronger events occur at lower altitudes, and therefore their optical emission is more obscured by clouds, and consequently undetectable. We saw in Figure 10, however, that this is not the case. While we tend not to see light associated with TIPPs which occur below 10 km, there is no indication that strong TIPPs are more optically attenuated by clouds. Second, if TIPPs are truly vertically oriented NBPs, they might be more readily detected from the limb of the Earth (if their radiation is beamed into a horizon lobe), and therefore tend to lie beyond the FORTE/OLS field of view. This, however, does not appear to be the case, because we saw that even for events seen by the FORTE/OLS, the percentage of events which are TIPPs drops dramatically at higher peak VHF power (Figure 8). Finally, strong TIPPs may simply be optically dark. This may indicate that VHF-powerful TIPPs are due to a different mechanism entirely than are weaker TIPPs. In that case, the change in percent optical coincidence reflects a critical peak power at which the TIPP distribution becomes predominantly made up of this new variety. This finding of optically dark lightning means that in the arena of space-based lightning observations there is an inherent complementarity between VHF and optical detection. Optical detectors can provide flash geolocation, while the VHF can probe all varieties of lightning in an unbiased manner.

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